Structural investigation of lattice and tubular steel wind turbine towers. A comparative study

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STRUCTURAL INVESTIGATION OF LATTICE AND TUBULAR STEEL WIND TURBINE TOWERS. A COMPARATIVE STUDY.

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ABSTRACT

Wind energy, being probably the most promising renewable energy source due to its great energy potential and applicability, concluded recently to a variety of impressive relevant structural applications. The most common type to support on-shore wind energy converters is the cylindrical steel tower. Research on the structural optimization of wind turbine towers is of great interest and importance due to their high manufacturing and erection costs and certain transportation limitations that prevent them from reaching greater heights. In order to increase the wind energy harvesting, the construction of taller structures and the improvement of their structural detailing is critical towards achieving greater energy production along with economy in material use and structural robustness. The present paper addresses the comparison of a classic tapered steel wind turbine tower with a hybrid lattice tower of the same height and energy production potential. Aiming to contribute to a better understanding of the structural behaviour of both types of wind turbine towers, the research work focuses on the development of reliable numerical models along with the use of analytical equations in order to predict accurately and interpret the aforementioned structural response of the two towers by conducting a comparative study between them. The present study examines the performance of each tower while attempting to minimize the total material used maintaining its endurance and robustness.

NOMENCLATURE

P	=	Total loads acting on a wind turbine
V	=	Vertical loading due to the nacelle weight (N)
H	=	Horizontal loading due to nacelle function (N)
M	=	Moment due to the rotor function (Nm)
W	=	Distributed loading on the tower shell (kN/m^2)

1. INTRODUCTION

Sustainable energy production is considered crucial in order to improve the current climate conditions and limit the use of fossil fuels that are finite and produce harmful emissions. Wind energy due to its infinite nature and due to its remarkable development during the past decades is a rather promising renewable energy source and therefore, research towards that direction is beneficial to the overall energy production. The optimized design of a wind turbine tower, being the basic structural part of a wind converter is of great importance in order to achieve more robust structures and more economic design. The most common wind turbine tower structural configurations are the cylindrical tower, the jacket one with a truss structure and the hybrid one in the sense of a combination of a truss structure for the lower part and a tube part for the upper one.

The most common wind turbine tower configuration is a steel cylindrical shell tower due to its robust structural detailing, easier mounting and limited labour done on site since the tower modules are manufactured in the factory and are only assembled on site. The tower is composed of subsequent cylindrical or conical parts that are transported and mounted on site [1]. The structural analysis of the main supporting structure of wind generators is considered of high importance since failure in such projects has great economical, structural and safety losses. The governing loads acting on the tower are the wind pressure up the tower height, the moment and the lateral load due to the rotor operation and the vertical load that is equal to the rotor weight. The classic tubular wind turbine tower is a simple cantilever structure, which due to its geometry can carry great loads with small shell thickness. The investigation of the buckling behavior of cylindrical shells has been founded by the research work, both numerical and experimental, conducted in the past by Timoshenko and Gere [2], Bazant and Cedolin [3], Teng and Rotter [4] and a plethora of other researchers. Tubular steel wind turbine towers belong to the area of cylindrical shells under combined loading and special research work has been devoted to the behavioral analysis of those structures and the explanation of their main structural problems [5]. Lee and Bang [6] elaborated a finite element model to simulate the collapse of an actual wind turbine tower whilst Arasu *et al* [7] and Nuta *et al* [8] have performed seismic analyses of wind turbine towers. Towards taking advantage of the higher energy potential at greater heights, wind converters tend to become taller and taller. Certain transportation limitations prevent the towers to have greater cylinder diameters and longer tower subparts. The solution of lattice towers has been till now implemented on telecommunication masts mostly and its structural behaviour has been investigated by Tsitlakidou *et al.* [9] and Efthymiou *et al.* [10]. Conventional lattice towers are constructed mostly with the use of standard L shaped cross sections fabricated in the factory and mounted on site. The scale of the lattice towers which are able to support the rotor of a wind converter leads to cross sections that are well outside the range of standard industrial profiles. A lattice tower that is capable of accommodating the nacelle or a cylindrical transformation element has the form of a truncated cone with a polygon or square cross-section. The tower is a statically determinate lattice structure composed of a number of discrete structural sub-systems; the legs, the bracing trusses on the faces, horizontal braces and secondary bracings arranged inside the plane of the face bracing trusses. The aforementioned structural subsystems have a particular role in the load transfer mechanism that develops inside a lattice tower and since the tower is a statically determinate structure, the axial stresses of the legs and the bracings can be determined by closed form expressions. The present paper addresses the stability performance comparison of a tubular steel wind turbine tower and a lattice wind turbine tower of the same height and with the same loading applied at the hub height. It examines the performance of each tower while attempting to minimize the total material used maintaining its endurance and robustness.

2. METHODOLOGY

The wind turbine tower that is used for the comparative study of wind turbine tower design has a total hub height of 76.15 meters. The tubular tower consists of 3 parts that are assembled on site due to transportation limitation of longer elements. The tower is modelled with reduced integration shell elements S4R as described in the software manual [12]. The original constructed tower is divided in 3 different parts of lengths 21.8 m, 26.6 m and 27.8 m from bottom to top. The lower diameter of the tower is 4.3 m and the top one is 3 m. The thickness of the shell wall is not constant, ranging from 30mm at the bottom to 12mm at the top. In the numerical model, the concentrated loads are applied at the top of the tower to a reference point eccentrically set to the middle axis of the tower, simulating the exact position of the rotor. The gravity loads are automatically calculated through the density of the material and the wind loading is taken into account as a distributed load along the tower height. The loads acting on the wind turbine tower are given in equation (1) and are: the vertical loading due to the nacelle weight (V), the horizontal loading (H) and moment (M) due to the rotor function and the distributed wind loading (W) on the tower shell.

$$P = \{V + H + M + W\} \tag{1}$$

The lattice tower used for the comparative study shares the same height as the tubular one. As explained above the structural sub-systems that the tower consists of have distinct roles in the load transfer mechanism of the tower. Therefore, each sub-system is investigated and optimized separately. The optimal face bracing truss is the V shaped and in order to minimize the total weight of the structure while maintaining its load bearing capacity the angle of the diagonals needs to be determined. For the presented investigation, the V brace angle is set to 45 degrees and in the Mathematica script used to calculate the optimal cross-sections secondary braces are allowed to be used. After determining the optimal diagonal angle, the only parameters needed to be characterized are the top and bottom width of the face of the tower. The two antagonistic factors that play a role in the optimal tower design at this point are:

- The parallel increase of the leg axial force along with the reduction of the face bracing weight, when closing the distance between the legs
- The parallel reduction of the leg axial force along with the total length and slenderness increase of the V braces, when increasing the distance between the legs

Since the determination of the optimal tower weight is not only dependant on the width of the tower at the top, but also by the buckling checks which is a highly non-linear procedure, a two dimensional search is demanded in order to assess the variation of the two independent parameters; B_{top} and μ. The second parameter is defined as the top tower width over the base tower width as shown in equation 2.

$$\mu = \frac{B_{top}}{B_{base,ch}} \qquad (2)$$

The script used for the optimal design of the tower uses a successive iterations scheme in order to converge to a final solution when total tower weight is minimum.

3. RESULTS

Regarding the tubular tower, material nonlinear analysis (Figure 1) is performed to examine the tower response towards this combined loading. The material data used in a non-linear analysis for steel S355 are: Poisson's coefficient 0.3, Young's modulus 210GPa and for steel class S355 the yield stress is considered 350MPa and ultimate strength 510MPa. In order to introduce plasticity data, the material properties have to be considered in terms of plastic true stress and plastic true strain. The tower shell thickness is optimized and a calculation of the total material used is also performed. The total tower mass is 127.215 tn, with the three tower subparts having 54.54 tn, 44.817 tn and 27.858 tn respectively from bottom to top.

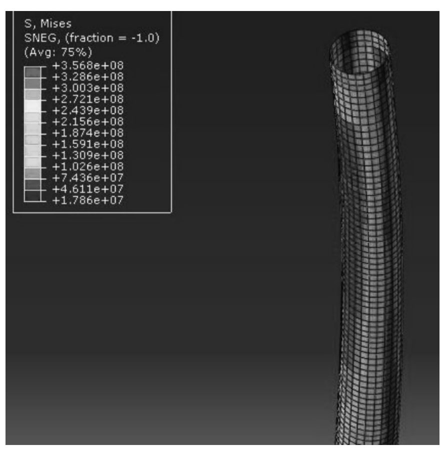

Figure 1. Tubular tower Material Non-linear Analysis.

The tubular tower subparts, in addition to having a tapered geometry, have also varying shell thickness from bottom to top. The thickness and geometry variation of the tower is presented in Table **2**1.

Table 3. Tubular tower diameter and thickness variation along the height

Height	Diameter	Thickness
0	4.3	0.03
4.4	4.2	0.026
8.8	4.1	0.027
13.2	4.0	0.023
22.0	3.8	0.022
28.6	3.7	0.020
39.6	3.5	0.018
45.6	3.4	0.016
54.35	3.3	0.014
63.15	3.2	0.013
71.95	3.0	0.012
74.15	3.0	0.014
76.15	3.0	0.018

As far as the lattice tower is concerned, all the tower subparts are designed and the optimum tower configuration is selected in order to minimize the total material used along with maintaining the tower load bearing capacity. The loads used for both the tubular and lattice tower are the same. The total number of cases investigated in order to optimize tower weight, are 126. The total weight for the optimal lattice tower solution is 77.47 tn. The lattice tower is lighter compared to the tubular tower for the selected hub height and critical assumptions can be made towards wind turbine tower optimal design based on the results presented in the following figures; (Figure 2), (Figure 3) and (Figure 4).

The braces used for the lattice tower are of V type, the V brace angle is set to 45 degrees and in the Mathematica script used to calculate the optimal cross-sections secondary braces are allowed to be used.

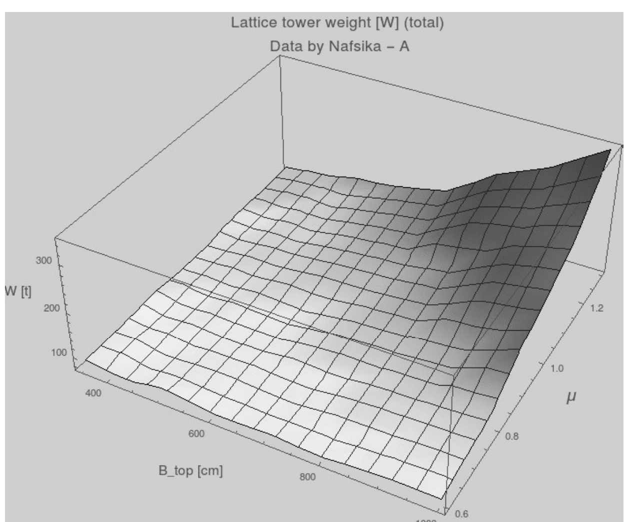

Figure 2. Total lattice tower weight in comparison to the top tower width and μ.

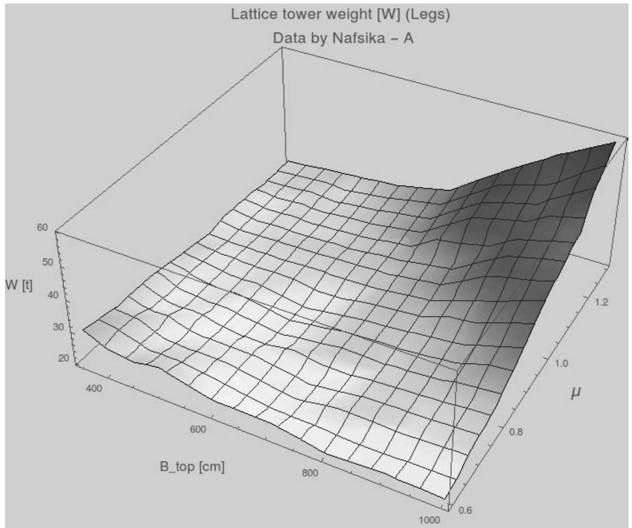

Figure 3. Tower leg weight in comparison to the top tower width and μ.

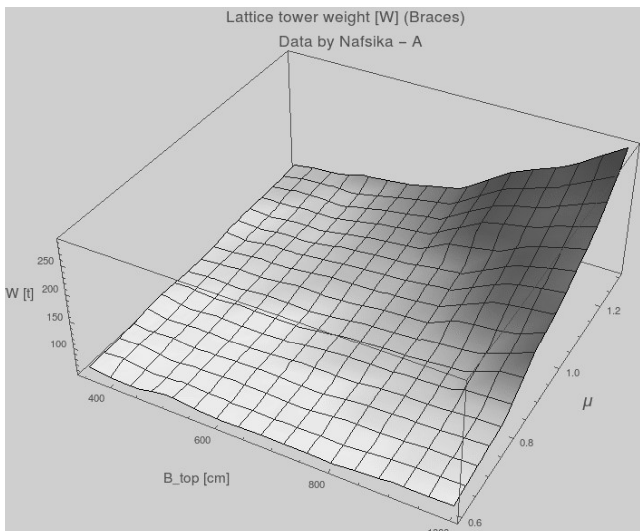

Figure 4. Braces' weight in comparison to the top tower width and μ.

The lattice tower is also divided in five levels, according to the height of the V-braces. The heights of the V-braces top elements and therefore the lattice tower subparts height is presented in Table 22.

Table 2. Lattice tower subpart heights

Tower subpart heights (m)					
Height	P-1	P-2	P-3	P-4	P-5
Subpart Height	34.45	55.53	68.19	75.64	76.15

As the tower is symmetric and the wind load can come from any direction, in each tower subpart the same type of elements are selected to have the same cross-sections. In our case circular hollow cross-sections are used and the optimal tower design is presented in Table 23.

Table 3. Lattice tower cross sections

Diameter and thickness of tower cross-sections (mm)					
Legs	P-1	P-2	P-3	P-4	P-5
Diameter	411	371	352	340	286
Thickness	8	8	7	7	5
V-Brace Diagonals	P-1	P-2	P-3	P-4	P-5
Diameter	413	385	375	363	253
Thickness	7	7	7	7	5
V-Brace Horizontals	P-1	P-2	P-3	P-4	P-5
Diameter	342	282	240	216	214
Thickness	6	5	5	4	4

The tower is almost 30 % of the initial construction cost of a wind turbine. Therefore, the reduction of the material used is of great importance in the economical aspect. As it can be observed from the comparison of the results of the two tower solutions, the total tower weight, using the lattice solution, is reduced by almost 40 %. Taking also into account the fact that in terms of transportation and in-situ construction, the lattice solution is advantageous in regards to flexibility in transportation and easiness in mounting, the lattice solution should be taken into consideration for the construction of contemporary wind turbines.

4. CONCLUSIONS

The present study investigates the potential of substituting tubular wind turbine towers with lattice ones with the project of minimizing the total structure weight while maintaining the structure load bearing capacity. With the prospect of constructing even taller structures, the minimization of the total material use is of great importance along with the transportation advantages that truss structures exhibit over the tubular ones. Cylindrical shells have been proven to be robust enough, offering higher capacity to the structure, but substantially greater amounts of material use. On the other hand, lattice structures when using the appropriate cross-sections for construction of tall structures are proved to be able to sustain great loads with minimum initial material weight. In the present comparative study, a wind turbine of 76.15 meters height has benn designed using both the tubular and the lattice solution. The design loads are identical in both types and the respective solutions are proven robust enough. In terms of total weight, the lattice tower is 40% lighter, minimizing by almost 15% the total initial construction cost. The advantages that the lattice solution offers in terms of transportation and fabrication, along with the flexibility of its configuration may lead to great and advantageous changes in the configuration concept in wind turbine tower design.

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